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Large-scale wind energy potential of the Caribbean region using near-surface reanalysis data

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A B S T R A C T

The lack of dense, high quality, long-term in-situ wind data sets and wind resource maps for the Caribbean region is a major impediment to the development of wind energy projects. Thus, there is limited understanding of the large-scale near-surface wind climate and the regional wind resources. Through statistical analyses on 10 m level NCEP/DOE reanalysis wind data for the period 1979–2010, this work found that although the prevailing winds are from the east-north-east over the eastern Caribbean islands, their wind direction distributions are bimodal. The regional area-averaged wind speed attains a maximum in January and a secondary maximum in July which coincides with the Caribbean Mid-Summer Drought. The derived regional annual wind resource map shows that the Caribbean low-level jet (CLLJ) region is an area of superb wind power density (WPD), 400–600 W/m^2, the eastern Caribbean and the Netherland Antilles are locations of excellent resource, 300–400 W/m^2, and the Greater Antilles and the Bahamas are areas of good-very good resource, 200–300 W/m^2. In general, WPDs are greater in the dry season than the wet season. The regional mean annual area-averaged WPD is 308 W/m^2 with mean WPDs of 350 W/m^2 for the dry season, 290 W/m^2 for the early rainy season, and 247 W/m^2 for the late rainy season. Annual WPDs vary within $\pm$ 18% of their mean. The area-averaged WPD ranges from 124 to 592 W/m^2 ($\pm$ 92% of mean annual WPD) depending on the year, season, or month. Therefore, the reanalysis data are shown to be suitable for general assessments of the wind resources in the Caribbean and thus, may be used as initial and boundary conditions in numerical models for the development of high resolution wind maps through dynamical downscaling.

Contents

Abbreviations: AGL, above ground level; CLLJ, Caribbean low-level jet; CREDP, Caribbean Renewable Energy Development Project; DOE, US Department of Energy; ECMWF, European Centre for Medium-Range Weather Forecasts; ENSO, El Niño – Southern Oscillation; ERS, early rainy season; ITCZ, Intertropical Convergence Zone; LRS, late rainy season; ML, maximum likelihood; NAH, North Atlantic High; NCEP, National Center for Environmental Prediction; PV, photovoltaic; SST, sea surface temperature; pdf, probability density function; WPD, wind power density

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1. Introduction

Caribbean small islands, because of their close equatorial location and alignment with the regional north-east trade wind system, are prime candidates for the use of a mixture of renewable energy technologies such as photovoltaic arrays and wind turbines. Trinidad and Tobago is the only Caribbean small island state with sufficient reserves of oil and gas for local consumption and for export. The remaining islands depend heavily on fossil fuel imports; for example, Barbados imports fossil fuels for 86% of their energy needs [1], while Jamaica imports 91% of its energy demand [2] and the Dominican Republic has a 78% dependency on imported oil [1]. Caribbean islands have pursued the use of renewable energy technologies because of this high dependence on energy imports. Over 23,000 solar water heaters have been in operation in Barbados since the 1970s due to fiscal incentives offered by the government [3,4]. However, the current cost of photovoltaic (PV) technologies makes it difficult to implement large-scale solar farms. Electricity generated from a wind turbine is cheaper than the PV counterpart [5,6]. For this reason, some of the Caribbean islands including Curaçao, Jamaica, Martinique and Guadeloupe have implemented wind energy technologies [7].

The Caribbean Renewable Energy Development Project (CREDP) has identified the lack of knowledge of wind resources as a barrier in development of wind energy projects in the Caribbean region [8]. The regional quantification of the wind resources could provide a reasonable estimate of the available wind power in regions such as the Caribbean where there is a lack of dense, high-quality in-situ data sets of long time periods and wind resource maps [9,10]. Previous studies by Elliott [11] and Elliott et al. [12] addressed the quantification of the wind resource in the Caribbean using ship data and interpolation-extrapolation based techniques in conjunction with land-based upper air data and surface data to derive land-based wind resources. Ship data have several limitations. Firstly, over 80% of the wind speeds from ships were estimated rather than directly measured [12]. Thus, large errors in the wind speed will be tripled in the wind power potential estimates. Secondly, the ship wind data were of monthly temporal resolution and do not account for the influence of daily and sub-daily wind speed variations on wind power density. Thirdly, the number of ship observations is dependent on ship travel paths and the frequency, and may not be spatially and temporally homogeneous. Homogeneity in wind data is a requirement for establishing the wind climate. In addition, the ship data used in [12] were for the time frame 1940s to 1970 and there is no in-depth study on the current wind climate that is relevant to the promotion and use of wind energy technologies in the Caribbean especially during this period of rapid increase in the use of wind energy technologies globally.

Therefore, alternative data sources must be explored. Since Elliott et al. [12] study, other data sets have become available, e.g. satellite data and reanalysis data. Satellite data have been used for investigating the large-scale wind energy potential for the world [13–15]. Satellite data are a good alternative and have the distinct advantage of higher resolutions over other types of data such as reanalysis data. However, one should note that satellite winds are inferred from the ocean roughness state [13,16]. The derived surface wind speeds may not be accurate since the signal may be quenched by thick clouds or heavy precipitation [17] which is prevalent in tropical regions such as the Caribbean, especially during the rainy season. Prior to analysis, observations contaminated by precipitation are removed, and may result in overestimating mean wind speeds. In addition, the atmosphere is assumed to be neutrally stable, introducing a bias during unstable and stable conditions. Furthermore, satellite data may not contain sufficient number of passes over a region for the computation of the wind resources [17].

Reanalysis data, which represent an assimilated form of land based meteorological station, buoy, ship and satellite data [18–20] into a general circulation model, may provide a more accurate representation of the large-scale wind resources of the Caribbean region. They are gridded and quality controlled allowing for a mapping of the wind resource on the large-scale and for the identification of potential areas of high wind resource. Reanalysis data span longer time periods than satellite datasets over higher resolution time periods. For example, the National Center for Environmental Prediction (NCEP)/Department of Energy (DOE) Reanalysis [20] provides wind components four times daily from 1979 which allow for a better representation of the wind speed probability distributions. In addition, the temporal and spatial homogeneity of the reanalysis data makes it more reliable for determining the wind climate and for assessing the influence of inter-annual variability on the wind resources. Reanalysis data have been used to study wind resources in Europe [21] and over the United States [22,23], investigate the stationarity in the wind statistics over the Baltic region [24] and climatic trends in wind speeds over the United States [25], assess high altitude wind energy globally [26] and over south east Europe [27], establish the current wind climate in climate change projection studies as in [28], and determine how spatial distribution of wind power plants reduces electrical grid variability [29].

Thus far, there has been no in-depth study for the Caribbean region using the reanalysis data sets to establish the wind climatology and the regional wind resource. Furthermore, no previous work on the Caribbean wind resources has quantified the wind potential

Nomenclature

A	wind turbine blade sweep area
E	wind power density described by the Weibull pdf
P	power
P_D	power density
N	number of data points
R^2	coefficient of determination
U	wind speed
$\langle U \rangle$	mean wind speed
c	scale parameter
f	probability density function
k	shape parameter
u	zonal wind component
v	meridional wind component

Greek Symbols

Γ	gamma function
ρ	air density
σ	variance in wind speed

for the natural seasonal division which comprises of two seasons: dry and wet. The dry and wet seasons are considered in policy and planning activities such as water resources management and agricultural planning and management [30]. In addition, the influence of inter-annual variability on the Caribbean wind potential has not been investigated.

This work therefore addresses the wind climatology and the regional quantification of wind power potential over the Caribbean region for the natural seasonal division using reanalysis data and investigates the influence of inter-annual variability on the wind resource. We have therefore described the study region, the reanalysis data, and the methodology in Section 2, characterized and discussed the large-scale near-surface wind climate and the regional wind resources, their respective states during the natural dry and wet season divisions found in the trade-wind Caribbean, and their year-to-year variations in Section 3, and presented our conclusions and recommendations in Section 4.

2. Study region and methodology

2.1. Caribbean geography and climatology

The Caribbean islands, located in the Caribbean Sea, stretch from Florida to eastern Venezuela (refer to Fig. 1). The northernmost islands of Jamaica, Cuba, Hispañola (Haiti and Dominican Republic), and Puerto Rico are referred to as the Greater Antilles. The Lesser Antilles is comprised of the smaller islands extending from Trinidad and Tobago in the south to the Virgin Islands. The majority of the Caribbean countries are located between 10°N and

Fig. 1. Map of the Caribbean region [32].

30°N. They experience equatorial and tropical marine climates which are generally hot and humid. The main variation is in the seasonality of the rainfall. The north-east trades are the prevailing winds in the Caribbean. The trade wind belts are located mainly between 5°N and 30°N. The Caribbean's weather is affected by the North Atlantic High (NAH), tropical waves, hurricanes, cold fronts and the inter-tropical convergence zone (ITCZ). The majority of the Caribbean islands are not under the direct influence of the ITCZ [31]. The ITCZ directly affects the most southerly islands and the northern South American continent.

Over the Atlantic, the North Atlantic subtropical High (NAH) produces strong trades from the north-east over the eastern Caribbean. Subsidence, stable sinking air, connected with the Azores high and the associated strong trades are the main mechanisms influencing the seasonal precipitation [31,33]. The NAH moves closer to the Caribbean during December–March enhancing the strength of the easterly trades. Strong inversions and cool sea surface temperatures (SSTs) lead to reduced atmospheric humidity. The rainy season is allied with a weakening of the NAH, weakened trade winds, increased convergence and the movement of the equatorial trough to higher latitudes. Other forcing mechanisms on Caribbean rainfall include sea surface temperature anomalies in both the Atlantic and the Pacific [34] and the El Niño Southern Oscillation (ENSO) [33,35,36]. These influence the inter-annual variability of precipitation and the timing of the start and end of the seasons.

The Caribbean generally experiences two seasons: the wet (or rainy) season, May to November, and the dry season, December to April. The monthly rainfall has an initial peak between May and June and a second between September and October [37]. The second peak is associated with the passage of tropical storms and hurricanes that develop from wave-like disturbances. These disturbances or tropical waves occur more frequently between June and early October. The wet season may be further subdivided into two seasons. The early rainy season (ERS) may be taken as the period May–July and the late rainy season (LRS) as August–November [38]. On a sub-regional scale, topography and elevation also modify the large-scale climate.

2.2. Global climatic data archives as input for the generation of a wind map

Reanalysis data are homogenized data sets derived from the assimilation of land surface, ship, rawinsonde, pibal, aircraft, buoy and satellite into general circulation models. The reanalysis data are ideal for the analysis of wind speeds in the Caribbean region since in situ surface data are generally sparse and infrequent in tropical regions, especially over the ocean. The US National Center for Environmental Prediction – National Center for Atmospheric Research (NCEP–NCAR) [18,19] and the European Centre for Medium-Range Weather Forecasts (ECMWF) developed reanalysis projects [39]. In this work, four-times daily 10 m wind speeds are used because the flow that influences wind energy usage is in the lower atmospheric boundary layer. Wind speeds were retrieved from the NCEP/Department of Energy (DOE) Reanalysis [20] archive. The NCEP/DOE reanalysis data are preferred to the ECMWF reanalyses which have shown spurious discontinuities in temperatures in the tropics in 1986 and 1989 with changes in the satellite observing system [40]. Inaccurate estimates of temperatures are likely to be accompanied by inaccurate estimates of wind speeds. In addition, NCEP/DOE reanalyses are used in preference to the NCEP/NCAR reanalyses since the NCEP/DOE reanalyses are produced from a general circulation model which is similar to that of the NCEP/NCAR but is an upgraded version with known errors fixed [20]. Wind speeds were derived from the zonal (u) and meridional (v) wind components at 00, 06, 12, and 18 UTC daily on an approximate 1.875° × 1.875° Gaussian grid. The wind data selected span the period January 1, 1979 to December 31, 2010. The reanalysis data used are gridded time series of wind speeds for a domain extending from 0°N to 30°N and 100°W to 50°W, which is slightly larger than the Caribbean region. In this domain there are 512 grid points and thus 512 time series.

2.3. Wind index

Wind farm developers and planners make use of wind indices to determine time periods of above and below average energy outputs. Wind indices may also be used to define a 'normal' wind period as in [24,41]. The Danish wind index was used here since it is a statistical mean for a region that describes the ratio of the long-term average power to the wind power in a month or year. The Danish wind index, I, is defined as [41]:

$$I=\overline{\sum_{j=1}^{n}\frac{U_j^3}{U_{i\ldots k}^3}}\times 100 \tag{1}$$

where $j=1\ldots n$ indicates the time series for the entire time period from $j=1$ (corresponding to 1979) to $j=n$ (corresponding to 2010). The subscripts $i\ldots k$ refer to the ten-year normalization period used in this work (1979–1988, 1980–1989, 1981–1990 etc.). Any wind period having a wind index of 100 matches the long-term wind energy variation of the full data period from 1979 to 2010. As compared with the long-term winds, normalization periods with stronger winds will lie below the wind index of 100.

2.4. Wind speed probability distributions

Wind energy resources have traditionally been studied using wind speed frequency distributions. Past studies on modeling wind speed frequency distributions have found that the two-parameter Weibull distribution agrees well with frequency distributions of observed wind data, including those taken over water surfaces [14,42,43]. The Weibull probability density function (pdf) is used in this work to allow for comparison with previous studies using single point data in the Caribbean that employed this distribution [44–46], as well as with those studies using a Weibull fit to satellite data [14,15]. The two parameters used to describe the Weibull distribution are the dimensionless shape parameter, k, and the scale parameter, c. For a given c, an increase in the shape parameter leads to a wider range of wind speeds and higher wind speeds are observed. However, for a constant k, a decrease in c gives rise to a narrower frequency distribution. This results in a larger frequency of low wind speeds.

The Weibull pdf of wind speed, U, is given by [47]:

$$f(v)=\frac{k}{c}\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{2}$$

A primary assumption in the use of the Weibull pdf for wind speeds is that the Weibull pdf is representative for wind distributions in all directions.

2.5. Power density

The wind power (P) available from the wind is given by [47,48]:

$$P=\frac{1}{2}\rho AU^3 \tag{3}$$

where ρ is the density of the air, and A is the area swept out by the wind turbine blades that is perpendicular to the wind flow. Evidently, the power varies as the cube of the wind speed, provided that the mean air density is not a function of wind speed.

The wind power per unit area is referred to as the wind power density, P_D, and is the chosen measure of wind energy potential since it is independent of the area swept out by wind turbine blades [48]

$$P_D = \frac{P}{A} = \frac{1}{2}\rho U^3 \tag{4}$$

Local wind variation of a specific location would determine the selection of a wind turbine. The mean wind power density (E) for a site whose wind speed histogram could be modeled by the Weibull pdf, whether monthly or annually, is given by [47–49]:

$$E = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{5}$$

where Γ is the gamma function. Although air density is a function of pressure, temperature and humidity, its variation is not significant so that it greatly impacts the wind resource calculation [50]. The density of dry air at standard temperature 288 K and sea level pressure is 1.225 kg m^{-3}. This value was chosen to enable comparison of results of this work with previous studies that employed it in the computation of power densities.

The Weibull parameters are computed using the maximum likelihood (ML) method, and are validated from the mean and variance of the dataset. The mean, $\langle U \rangle$, and variance, σ, of the pdf are estimated from the Weibull parameters via [17]:

$$\langle U \rangle = c\Gamma\left(1+\frac{1}{k}\right), \tag{6}$$

and

$$\sigma^2 = c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]. \tag{7}$$

The ML method estimates the scale, c, and shape, k, parameters from the following [48,50]:

$$\hat{k} = \left[\frac{\sum_{i=1}^{N} U_i^{\hat{k}} \ln(U_i)}{\sum_{i=1}^{N} U_i^{\hat{k}}} - \frac{1}{N}\sum_{i=1}^{N} \ln(U_i)\right]^{-1} \tag{8}$$

$$\hat{c} = \left(\frac{1}{N}\sum_{i=1}^{N} U_i^{\hat{k}}\right)^{1/\hat{k}} \tag{9}$$

where N is the number of data points. Eq. (8) is solved for $\hat{k}$ through the application of an iterative solver. Each wind speed time series is assumed to follow the Weibull distribution. A fit to each of the 512 time series to the Weibull probability density function is determined by computing ML estimates of the shape, k, and scale, c, factors for each grid point using the R Statistics package.

3. Results and discussion

3.1. Near-surface wind climate: wind direction

3.1.1. Prevailing winds throughout the year

The most frequent wind directions over the wider Caribbean region are shown as vectors of unit length in Fig. 2. The prevailing winds in the Caribbean are mostly from the east-north-easterly direction over the eastern Caribbean and from the east over the western Caribbean. The predominantly east-north-easterly winds over the eastern Caribbean give rise to more northerly winds over the South American continent. The easterly winds over the western Caribbean lead to winds primarily from the north-east over Central America within the 10–20°N band and winds from the south-east in the 20–30°N band. Between 6° and 10 °N in the Pacific is a region consisting of north-easterly winds to the north and south-westerly winds to the south, and may mark the presence of the ITCZ. The predominant south-south-westerly winds along the western coast of Columbia become mainly westerly winds further inland and seem to be a low-level manifestation of the El CHOCO (Chorro del Occidente Colombiano, or western Colombian jet) which is well documented by Poveda and Mesa [51] and references therein.

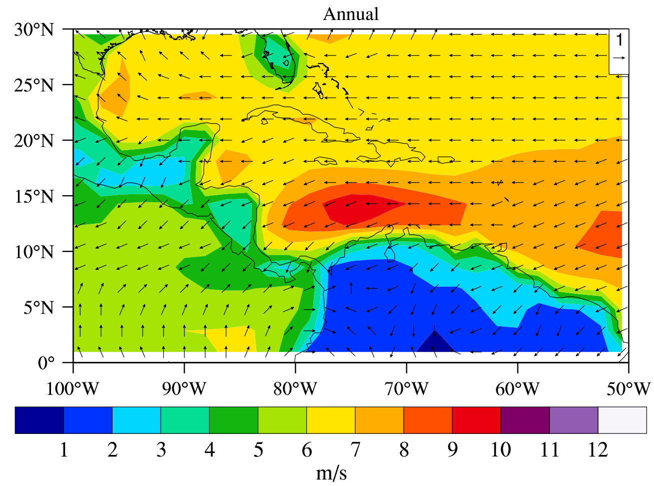

Fig. 2. Prevailing wind direction (arrows) and wind speed (m/s) (contours) for the period 1979–2010. All arrows are of unit length as they depict only prevailing wind direction and not wind speed.

3.1.2. Prevailing winds on seasonal and monthly scales

East-north-easterly winds observed over most of the Caribbean Sea, the Greater Antilles, and the Lesser Antilles during the dry season (Fig. 3(a)) become more easterly during the wet season (Fig. 3(b)). Considering the splitting of the wet season into an ERS and a LRS, these east-north-easterly winds prevail during both the ERS (Fig. 4(a)) and the LRS (Fig. 4(b)). Winds in the region between Cuba and the Central American continent are from the east in the ERS and east-north-east during the LRS.

There exist several sub-regional monthly variations in prevailing winds in the Caribbean. The Greater Antilles of the Caribbean experience winds from the east-north-east between October to April (Fig. 5) and easterly winds otherwise. Over the Lesser Antilles the prevailing winds are from the east-north-east between November and March and from the east for other months of the year. The east-north-easterly prevailing winds over the Caribbean Sea occurring between November and January undergo a slow spatial change to prevailing easterly winds which exist during June to October. The Bahamas islands experience easterly winds in February and May to September. Preliminary siting studies in well-exposed sites could make use of the fact that the large-scale prevailing winds during each month may not deviate from the east-north-easterly and the easterly directions throughout the Caribbean.

3.1.3. Directional variability in the winds in the Caribbean on an annual scale

The information derived from annual wind directional variability complements that of the prevailing winds. Wind directional variability at each grid-point is represented by a wind rose in Fig. 6. The annual east-north-easterly prevailing winds (Fig. 2) mask the directional distributions over the Lesser Antilles which are bimodal in nature, with similar frequencies for the east and east-north-east winds. Furthermore, for islands at latitudes greater

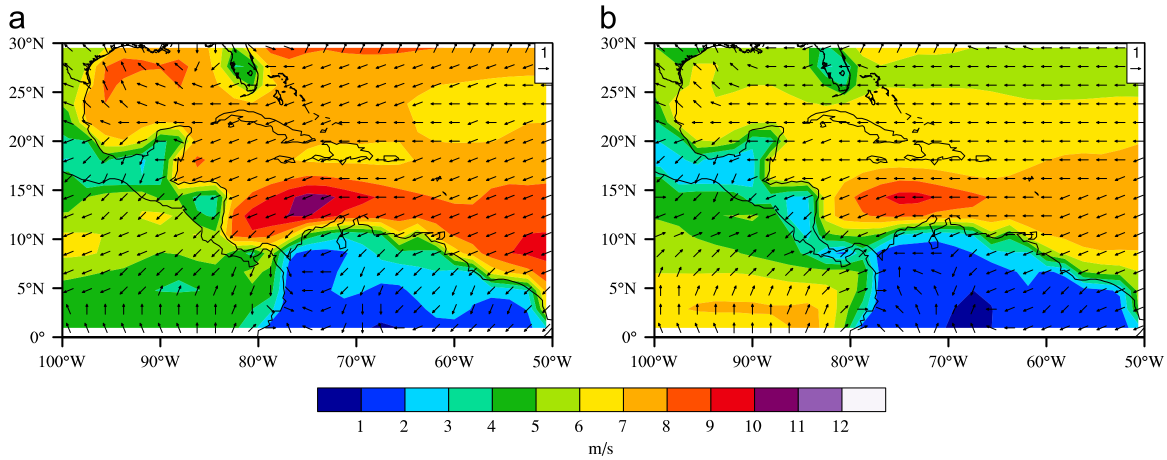

Fig. 3. Prevailing wind direction (arrows) and wind speed (m/s) (contours) for (a) dry season and (b) wet season for the period 1979–2010.

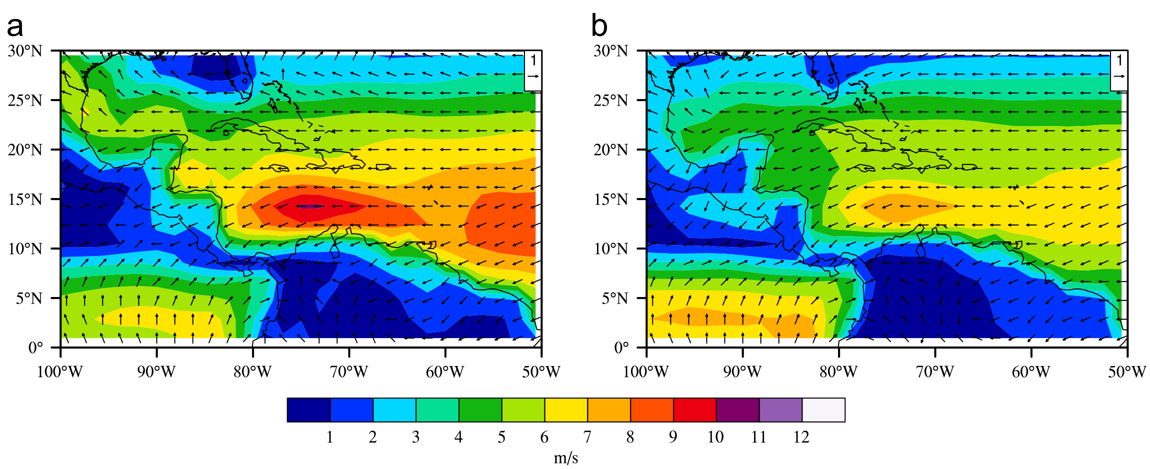

Fig. 4. Prevailing wind direction (arrows) and wind speed (m/s) (contours) for (a) ERS and (b) LRS over the period 1979–2010.

than 17°N, east-south-east winds become more frequent. The wind roses within the Caribbean have low dispersion highlighting the persistence of ENE and E winds throughout the year while wind roses at latitudes greater than 27°N as well as those over the South American continent have high dispersion.

3.2. Near-surface wind climate: average wind speeds

3.2.1. Annual mean wind speeds

Fig. 2 also shows the spatial variation of the annual wind speed over the Caribbean region. The highest wind speeds, between 8.0 m/s and 9.8 m/s, are experienced in the sub-region 12–16°N, 70–78°W from the northern coast of South America to Hispañola. This band of high wind speeds is associated with the Caribbean Low-Level Jet (CLLJ) which has maximum winds at the 925 hPa level and is documented at this level by [43–45]. The CLLJ has been identified in other forms of data e.g., satellite [15], although, not explicitly so. Although in the CLLJ region wind speed variability is higher in the wet season (Fig. 7), the CLLJ region may be suitable for regional wind farming because of its high mean wind speeds.

Moderately-high annual wind speeds in the range 7.0–8.0 m/s are experienced over the eastern Caribbean islands and also over the Leeward or Netherland Antilles (7.0–9.0 m/s). The Netherland Antilles and the eastern Caribbean small islands with their moderate-high seasonal mean wind speeds may benefit from the constant low wind speed variability over the annual cycle. These islands are possible good candidates for wind farms based on the 10 m reanalysis data. The Bahamas and the Greater Antilles experience winds in the range 6.0–7.0 m/s throughout the year. Cuba and the Bahamas have high wind speed variability in the dry season, moderate variability in the ERS and high variability in the LRS. In contrast, wind speed variability over Jamaica is not significantly different from one season to another (Fig. 7). Cuba and the Bahamas, because of the low wind speeds (Fig. 4) and the high variability (Fig. 7) during the LRS, and Jamaica with its low mean wind speed class in the LRS (5–6 m/s) coupled with moderate wind speed variability, may be less effective areas for wind farming during the LRS.

3.2.2. Seasonal wind speeds

Generally, wind speeds are stronger in the dry season than the wet season within the Caribbean region (Fig. 3). Wind speeds in the CLLJ region decrease to 7.0–9.5 m/s in the wet season while during the dry season they are between 7.5 m/s and 10.4 m/s. In the CLLJ region there is a distinct difference in maximum near-surface wind speeds between the ERS of 10.2 m/s and the LRS of 8.6 m/s. This is not the case between the dry season and the ERS. This indicates that the windy season may not necessarily coincide with the defined dry season.

We also note that the distinct difference between the ERS and the LRS and the similarities between the dry season and the ERS in mean wind speeds over the Netherland Antilles and the eastern Caribbean. Dry season wind speeds, 8–9 m/s, over the Netherland Antilles islands and the eastern Caribbean small islands, with the exception of the most southerly island of Trinidad, are stronger

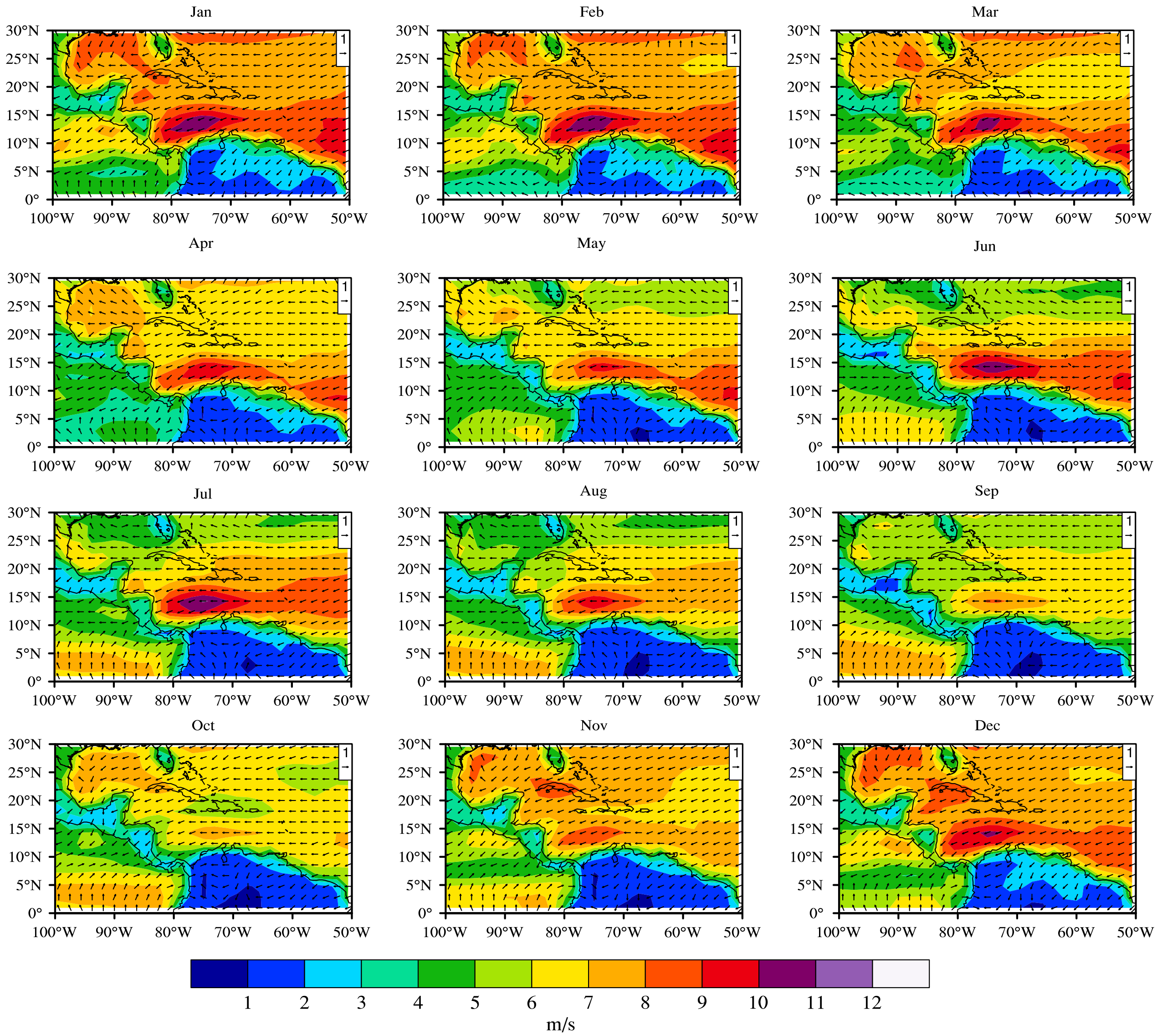

Fig. 5. Prevailing wind direction (arrows) and wind speed (m/s) (contours) for each month over the period 1979–2010.

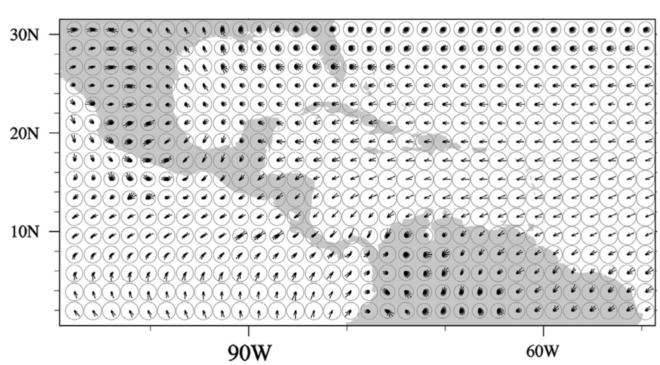

Fig. 6. Wind directional distribution represented by a wind rose for 1979–2010 at each grid-point.

than the wet season winds, 7–8 m/s. While wind speeds maintain this range in the ERS, they are in the 6–7 m/s range during the LRS.

In contrast, other sub-regions experience a progressive decrease in mean wind speeds as the year advances. Trinidad's wind speed class changes from 7–8 m/s (dry) to 6–7 m/s (ERS) to 5–6 m/s (LRS). Furthermore, non-adjacent sub-regions of the Caribbean have similar seasonal wind class variations such as Trinidad in the south and Jamaica in the north. Different sub-regions of the Caribbean undergo various changes in wind class when transitioning between seasons. Examples are Cuba, the Bahamas, Hispañola and Puerto Rico as indicated in Fig. 3 (a) and (b) during both the dry and wet seasons.

3.2.3. *Monthly mean wind speeds*

The monthly variation in the spatial wind speeds (Fig. 5) highlights the following: (1) The wind speeds in the CLLJ region are a minimum in May and October and a maximum in February and July; (2) The higher latitude ($>25°$N) lying islands in the Bahamas consistently experience low wind speeds from May to September but moderate winds otherwise; and (3) the Netherland Antilles islands experience moderate-high winds of 6.5–9.0 m/s throughout the year.

The monthly mean wind speeds support the shift in wind speed class described for seasonal classes in Section 3.2.2 for the Eastern Caribbean and the Greater Antilles islands. However, winds over these islands briefly intensify in June–July although the monthly variation indicates that there are decreases in wind speed class from the dry season to the ERS to the LRS. In addition, wind speeds begin to increase from November, one month prior to the

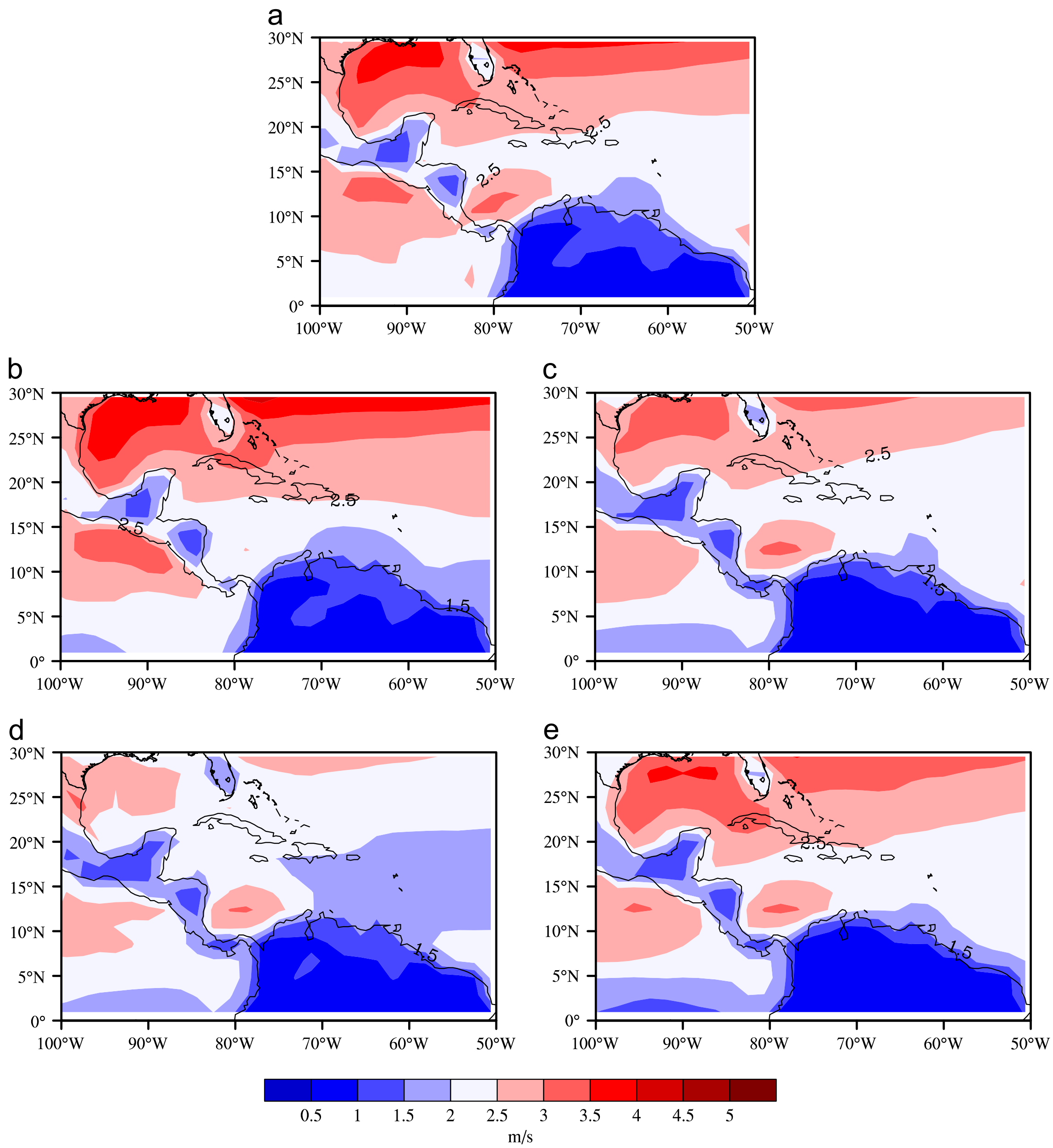

Fig. 7. Standard deviations in wind speeds (m/s) for annual, dry season, ERS and LRS.

start of the meteorological dry season. This observation implies that the windy season differs from the meteorological dry season and may have to be defined for the Caribbean region.

3.3. *Area-averaged wind speeds*

3.3.1. *Monthly variation*

The monthly variation in area-averaged wind speed summarizes the annual cycle of the wind climate in a region, and is depicted in Fig. 8 for the Caribbean. The area-averaged wind speed in the Caribbean attains a minimum of 5.8 m/s in September, a primary maximum of 7.8 m/s in January, and a secondary maximum of 7.1 m/s in July. We observe that the secondary maximum coincides with the occurrence of the Caribbean Mid-Summer Drought (MSD) during the rainy season, as well as it is also observed at the sub-regional level in the CLLJ region (refer to Section 3.2.3).

3.3.2. *Inter-annual variation*

A good indicator of wind potential is the range of annual averaged wind speed since it directly influences the inter-annual variation in wind power densities. The area-averaged wind speeds and the standard deviations in wind speeds in the Caribbean for each season are shown in Fig. 9. The mean wind speed for all years is 7 m/s while annual wind speeds vary between 6.5 and 7.4 m/s, which are within $\pm$ 7% of the mean wind speed. Wind speed standard deviation varies between 2.2 and 2.6 m/s. The region as a whole experiences moderate wind speeds. The annual area-averaged wind speeds indicate that there may be an increasing trend in Caribbean wind speeds. Annual wind speeds prior to 1995 are generally below average and after 1995, above average. An increasing trend in mean wind speeds accompanied by an increasing trend in standard deviation (Fig. 9) may lead to greater intra-annual variation in monthly wind power densities. Further investigation using rigorous statistical analyses for possible trends would be required to confirm a trend.

3.3.3. Inter-annual variation in seasonal wind speeds

Area-averaged wind speeds are higher during the dry season (6.8–8.0 m/s), as compared with the wet (ERS+LRS) season (6.5–7.6 m/s) (Fig. 9). Small island states with hydropower such as Dominica and St. Vincent [52] could supplement electricity production from wind energy sources during the dry season when hydropower production is not reliable [52]. In contrast, there is little difference in the area-averaged wind speeds between the ERS and the LRS. In addition, the annual variation in LRS area-averaged wind speeds and standard deviations seem to have a trend of increasing values. This is not apparent for the other seasons.

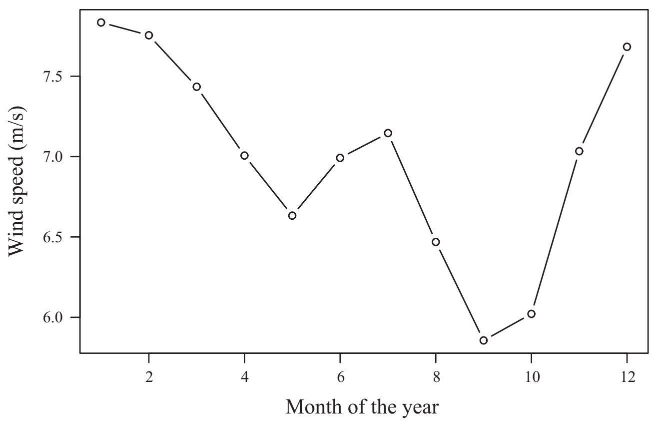

Fig. 8. Monthly variation of area-averaged wind speed (m/s) within the Caribbean.

3.4. Wind index

The long-term wind power from 1979 to 2010 is slightly more than the wind power for the normalization periods 1979–1988, 1980–1989,..., 1991–2000 (Fig. 10), that is, the wind indices are greater than 100. In contrast, the periods 1982–1991, 1992–2001, 1993–2002, 1994–2003, could be considered as 'normal' wind periods since their wind indices have deviations from the 'normal' wind index of 100 by less than $\pm 2.5\%$. Periods later than 1995 such as, 1995–2004, 1996–2005, etc., are periods of slightly stronger winds, up to 8% more than the long-term average.

One should note that during each of the 'normal' wind periods, 1982–1991, 1992–2001, 1993–2002, 1994–2003, there were between two and four ENSO events [53]. This is surprising since ENSO events are normally associated with anomalous climatic conditions. In the Caribbean, ENSO events are generally followed by drier late rainy seasons [30]. However, 'normal' conditions in this work are defined in terms of wind speeds only. A further analysis on the impact of ENSO events on the Caribbean wind

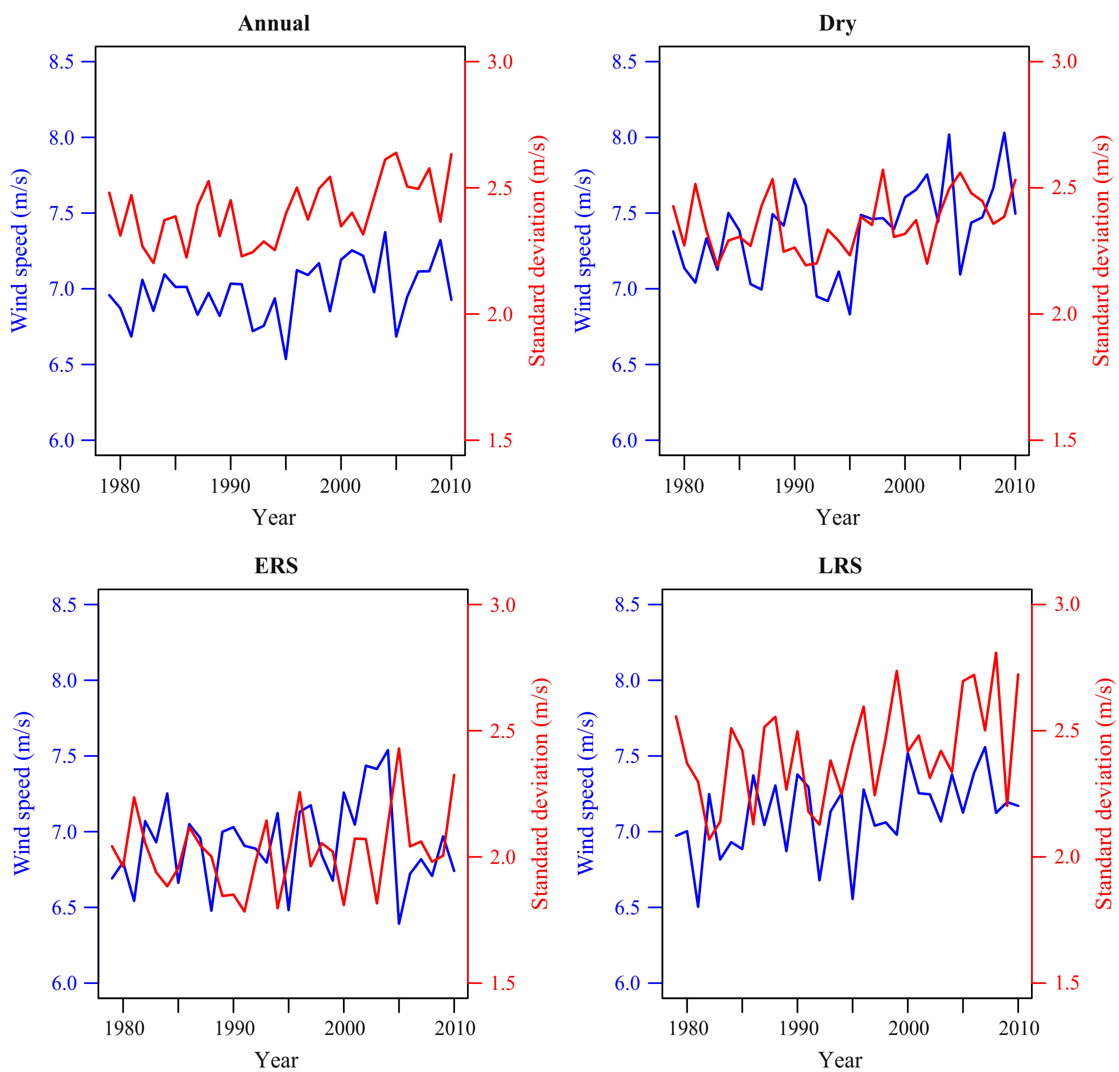

Fig. 9. Inter-annual variability of annual area-averaged wind speeds (m/s; blue line) and annual area-averaged standard deviation in wind speeds (m/s; red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

climate would be needed to determine why the specific periods were 'normal' wind periods since not all decades with ENSO events experience 'normal' wind conditions.

The variation of the wind index based on ten-year periods during 1979–2010 indicates that the available wind energy potential may be increasing. However, as in Section 3.4, no definite statement can be made without a rigorous trend analysis, which is outside the main objective of this study.

3.5. Weibull fits

The distribution of the observed wind speeds about the mean is necessary to estimate the wind energy potential since the wind is a highly variable meteorological parameter [54]. Fig. 11 (a) illustrates the wind speed distribution and the Weibull fit to the wind speed histogram at a randomly selected grid-point located in the Eastern Caribbean at 14.2855°N, 60.000°W. This grid-point is one degree longitude east of St. Lucia and is northwest of Barbados. For this location, the Weibull fit captures the actual distribution at all wind speeds, including the mode. The Weibull fits at all grid-points were checked by comparing the estimates of the wind speed mean from the Weibull distribution with actual sample mean (Fig. 11 (b)). Fig. 11 (c) is similar to Fig. 11 (b) but shows the variance estimated from the Weibull distribution vs. the sample variances. Fig. 11(b) and (c) show that the Weibull distribution is suitable for describing the distribution of wind speeds at all grid points because the mean and variance calculated from the Weibull distribution closely follow the actual mean and variance.

We also verify the suitability of the Weibull pdf to represent wind speed distributions at each grid-point by computing the unexplained variance $100(1-R^2)$ where R^2 is the coefficient of determination. Unexplained variance could reach as high as 30% over South America (Fig. 12), indicating the unsuitability of the Weibull pdf for wind speed distributions in areas of complex topography such as the Andes. However, the Weibull pdf is

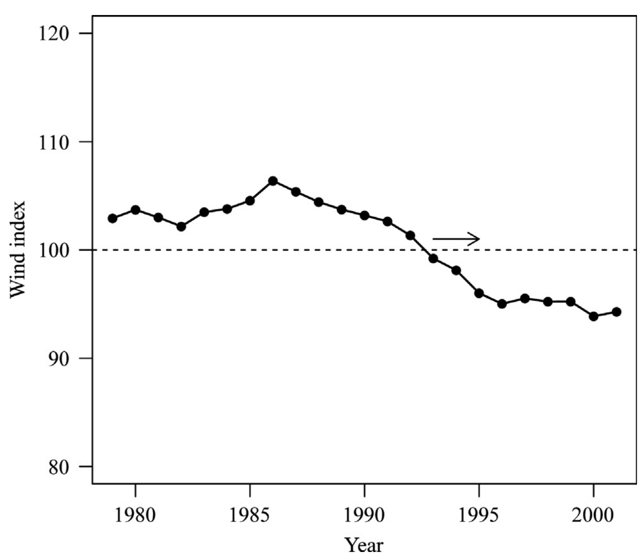

Fig. 10. Annual wind indices for the Caribbean. Arrow depicts the starting years of decadal periods with wind power content greater than the 1979–2010 period.

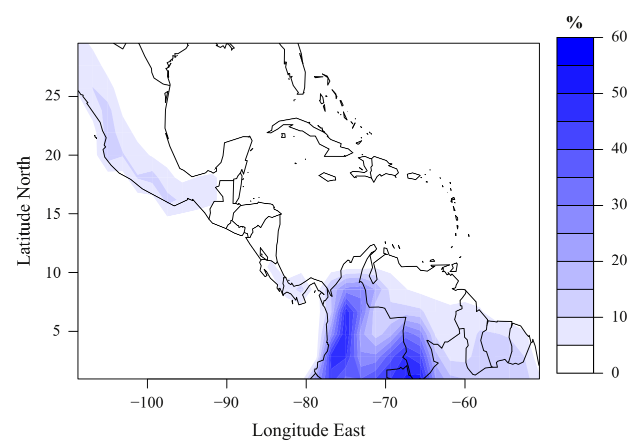

Fig. 12. Spatial variation in the percentage of unexplained variance of the Weibull pdf fits throughout the Caribbean.

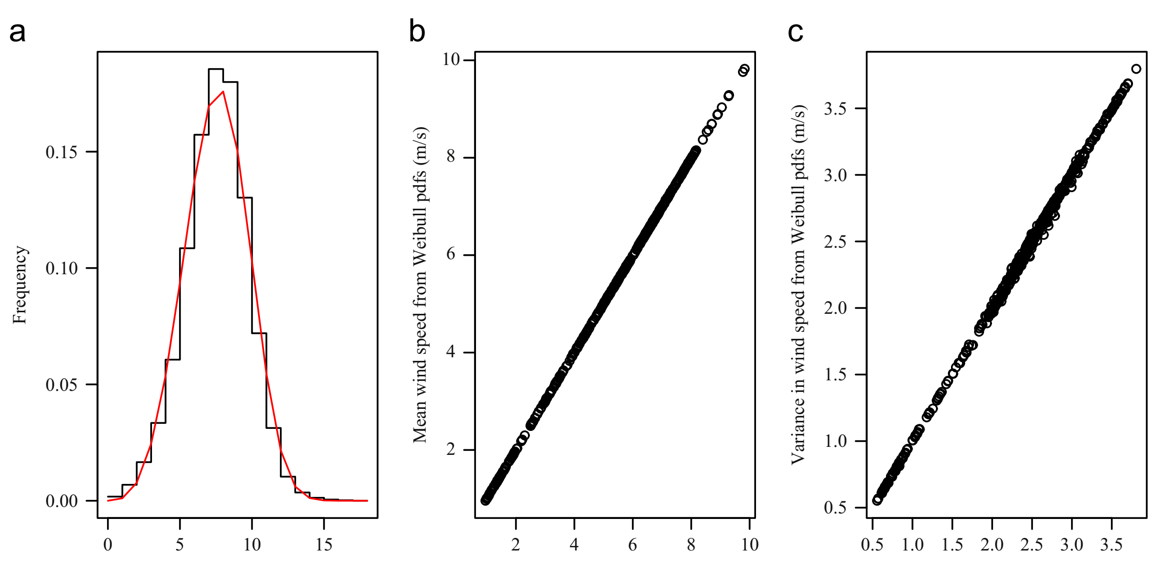

Fig. 11. (a) Sample wind speed distribution with bin size of 1.0 m/s fitted to a Weibull distribution, (b) mean wind speeds (m/s) calculated from the Weibull fits at each grid-point vs. mean wind speeds (m/s) calculated from the data, (c) standard deviations in wind speeds (m/s) calculated from the Weibull fits at each grid-point vs. standard deviations in wind speeds (m/s) calculated from the corresponding grid time-series.

suitable for wind speed distributions within the Caribbean as the unexplained variance in this region is less than 5%.

3.6. Wind power densities

3.6.1. Annual Weibull parameters and wind power densities

Wind power densities were computed for the region using Eq. (5), and the Weibull shape (k) and scale (c) parameters. The annual Weibull shape factor (k) (Fig. 13(a)) varies between 2 in the north of the Caribbean region and 5 in the south. The shape factor is an indicator of the width of the distribution. The larger the value of k, the narrower the distribution, and the smaller the spread of wind speeds about the mean.

Scale factors (Fig. 13(b)) vary between 6 and 8 m/s just off the north coast of South America, 7 and 8 m/s in the northern Caribbean, 9 and 11 m/s in the CLLJ region, and have values in the range 7–9 m/s in the eastern Caribbean. Since the scale factors are a reflection of mean wind speeds, they determine the range of the wind speed distribution. The larger the scale factor, the wider the range of wind speeds experienced, and the greater the mode wind speed. However, with a wider range of wind speeds, mode's frequency decreases.

The sub-region with the highest annual power density (Fig. 13(c)) is the CLLJ region with wind power potential in the range 400–700 W/m^2. The eastern Caribbean and the Gulf of Mexico experience moderate-high power densities of 300–350 W/m^2. The larger islands of Jamaica, Hispañola, Puerto Rico and the south-eastern tip of Cuba have moderate wind power potential between 200 and 300 W/m^2. The South American coastline has low-moderate energy potential, 100–300 W/m^2. Coastal Guyana has low-moderate potential of 100–200 W/m^2 annually while inland Guyana has low energy densities (< 100 W/m^2).

3.6.2. Seasonal and monthly mean wind power densities and their Interannual variations

The scale parameters (Fig. 14(a), (d) and (g)) are larger in the dry season than the ERS or LRS and follow a similar seasonal variation as the mean wind speed. The seasonal shape parameters for the dry season, ERS, and LRS (Fig. 14 (b), (e), and (h)) have two distinct features. Firstly, a wide band of high k ($4 < k < 6$) is present over the Atlantic Ocean and the Caribbean Sea during the dry season and ERS when compared with the LRS k spatial variation. This band is bounded by 10°N–15°N, 50°W–80°W in the eastern and southern Caribbean. In addition, the months defining wind seasonality may be different from that of rainfall seasonality since the dry season and the ERS spatial distribution of shape parameters are similar. Other sub-regions such as Cuba and the Bahamas do not show much variation in k values between seasons. The second feature in the k seasonal spatial distribution maps is that the eastern Pacific shows higher k values in the LRS, while there are lower k values in the Caribbean. As the year progresses, the wind distributions in the Pacific become narrower toward the latter part of the year while those in the Caribbean become wider. Wind speeds in the Atlantic and eastern Pacific seem to vary out-of-phase. This observation will warrant further investigation.

Seasonal variability should be accounted for in wind energy assessments. Wind power densities are higher in the dry season than in the ERS or LRS season as shown in Fig. 14 (c), (f), and (i). However, Jamaica, Hispañola, eastern Cuba, and the northern coastline of South America do not experience much change in the power density among the seasons.

The variations in regional average power density over the Caribbean region by seasons and months are shown in Figs. 15 and 16 respectively. The mean seasonal power densities are 350 W/m^2 for

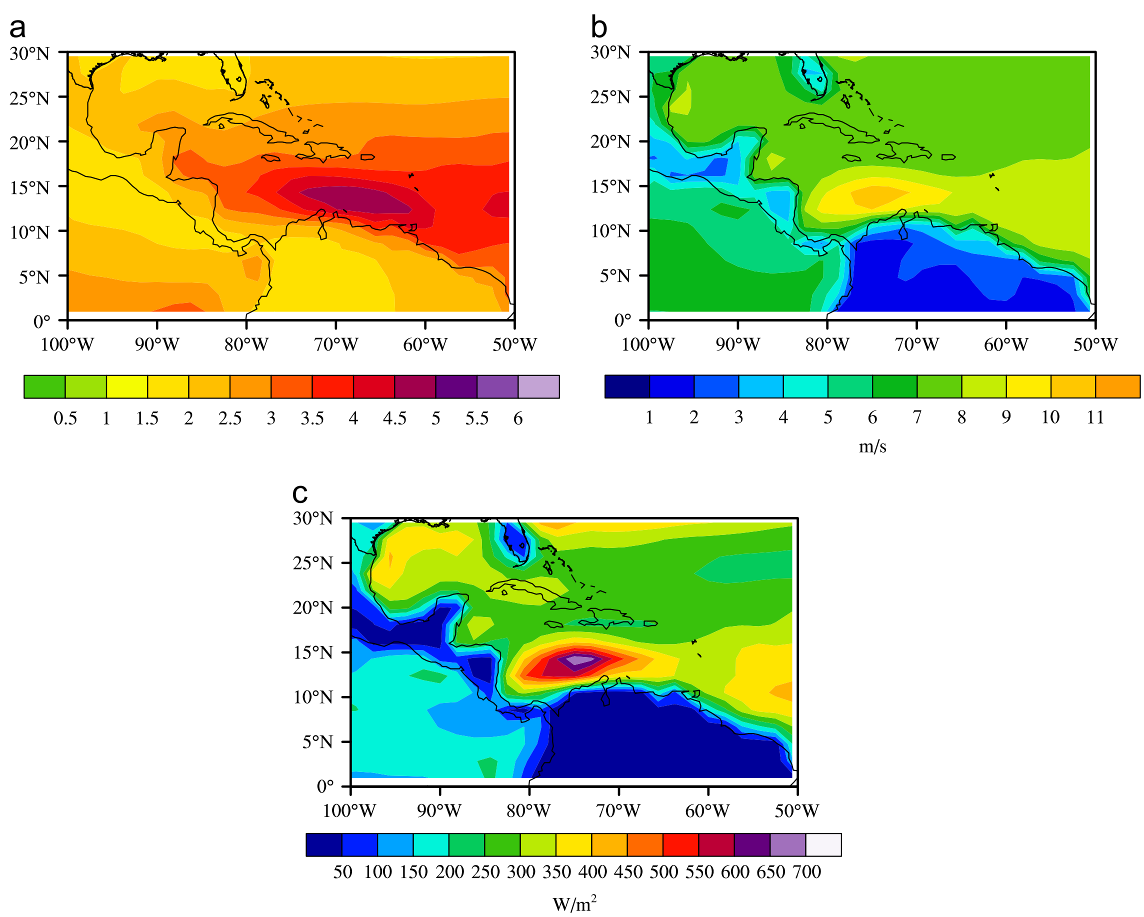

Fig. 13. (a) Weibull shape factor k, (b) weibull scale factor c in m/s, and (c) annual power density (W/m^2) for entire data set, 1979–2010.

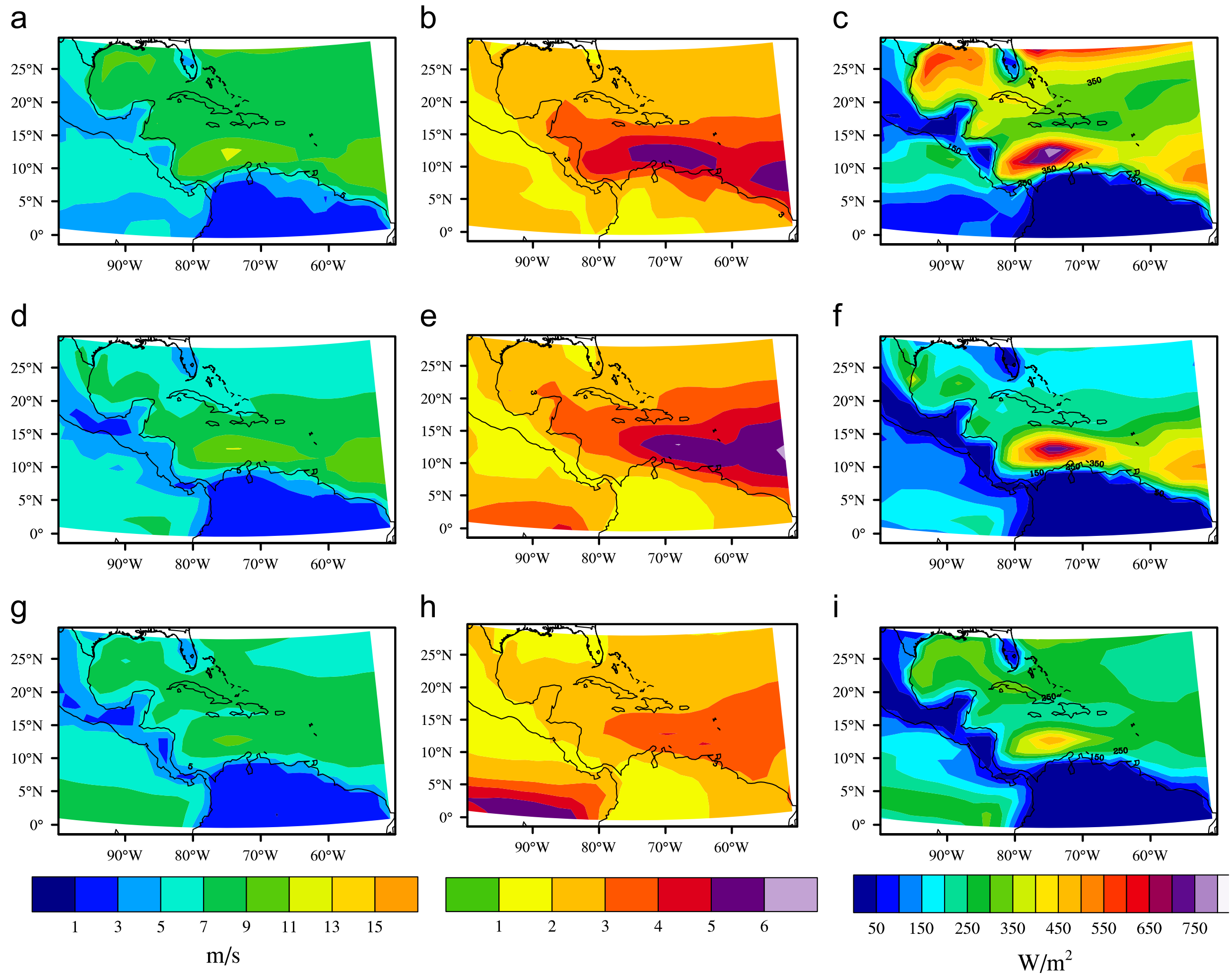

Fig. 14. Seasonal variations in the Weibull scale c (m/s) and shape k parameters, and the wind power density E (W/m^2). The first column (a, d, g) shows the scale parameters, c (m/s), for each season, the second column the corresponding shape parameters k (b, e, h) and the third column the power density E (W/m^2) (c, f, i). (a) Dry-Scale, (b) Dry-Shape, (c) Dry-Power Density, (d) ERS-Scale, (e) ERS-Shape, (f) ERS-Power Density, (g) LRS-Scale, (h) LRS-Shape, (i) LRS-Power Density.

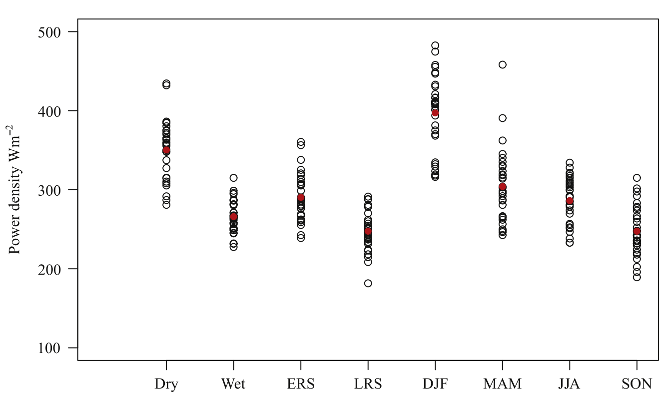

Fig. 15. Caribbean averaged wind power density by season in W/m^2. The red dots indicate the mean seasonal value. The black circles are the annual seasonal values for each year from 1979–2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

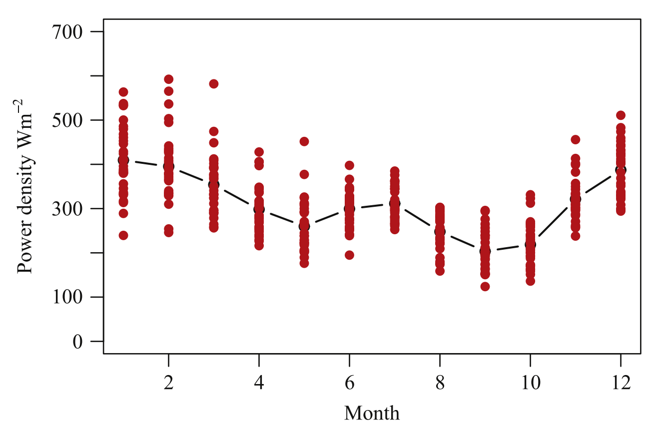

Fig. 16. Monthly variation in the power density E (W/m^2) for the Caribbean region. Each red dot represents the monthly power density for each year in the period 1979–2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the dry season, 290 W/m^2 for the ERS, and 247 W/m^2 for the LRS. The mean seasonal values represent a 13.6%, −5.8%, and −19.8% deviations from the annual mean of 308 W/m^2.

The energy content in the wind could vary significantly from one year to another. The annual WPDs are within ± 18% of the annual mean. Depending on the year in question for the 1979–2010 period, the mean wind power density was in the range 281–435 W/m^2, 239–361 W/m^2 for the ERS and 182–291 W/m^2 for the LRS. Thus, considering natural seasonal stratification, the minimum power density of the region is 182 W/m^2 while the maximum wind power density is 435 W/m^2, representing a −40.9% and 41.2% change from the annual mean of 308 W/m^2. On the other hand, a subdivision of the year according to the northern hemisphere seasons (December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON)) produces a slightly wider range in Caribbean wind power density, with minimum value

of 189 W/m^2 during SON and maximum value of 482 W/m^2 during DJF.

The monthly variation (Fig. 16) shows an even wider range of power densities, with a minimum value of 124 W/m^2 in September and a maximum value of 592 W/m^2 in February. Thus, the Caribbean regional power density varied between 124 W/m^2 and 592 W/m^2 when the influence of the inter-annual variability on seasonal and monthly power densities was considered. These values represent a change of −59.7% and 92.2% from the mean power density over the entire period considered. This supports the consideration of the influence of wind speed distributions on power densities at smaller temporal subdivisions than the seasonal counterpart, even for large-scale resources.

3.7. Comparison with previous studies utilizing single meteorological station data and satellite data

In this section, our regional quantification is compared with single-point wind resource assessment studies as well as with global studies using satellite data.

In general, the wind characteristics derived from reanalysis data agree reasonably well with the mean wind speeds, Weibull parameters, and power density for the Guyanese coastland as in [44]. Persaud et al. [44], using wind speed measurements at a coastal station in Guyana taken at 10.67 m above ground level (AGL) for the period 1971–1972, found that the annual mean wind speed, and the Weibull scale (c) and shape (k) parameters were 5.79 m/s, 7.08 m/s and 3.70, respectively. The corresponding parameters for this study fall in the 3–6 m/s, 5–7 m/s and 3.0–3.5 ranges, respectively. The annual WPD of [44] when corrected for standard air density was 165 W/m^2 and lies within this study's range of 100–200 W/m^2.

Weisser [45] reported that the seasonal WPDs at a Point Salines coastal station in Grenada (12°1′N, 61°13′W) for 1996–1997 were 160 W/m^2 for the dry season (defined as December-May) and 100 W/m^2 for the rainy (wet) season. The mean WPD over Grenada was found to be 350–400 W/m^2 during the dry season (December–April) and the ERS, and 200–300 W/m^2 in the LRS. Although this study reproduces the decrease in WPD in the wet season, the WPD ranges are a factor of two higher than Weisser's study and may be due to 10 m reanalysis winds being compared with wind measurements taken at 7 m AGL at Point Salines. Other factors contributing to why the calculated power densities here are a factor two off are the reanalysis' GCM inability to account for the influence of Grenada on large-scale winds because of its low horizontal resolutions, and the differences in the definition of the dry season.

Although the GCM that produced the NCEP/DOE reanalysis has low resolution and is unable to account for the effects of a small island on large-scale winds, the 10 m reanalysis winds are representative of low-level synoptic winds over the fairly flat island of Barbados. Wind measurements in Lamberts East were taken at 55 m AGL [46]. By using the reported measured mean wind speed and standard deviation, and Eq. (2) in [46], we found that the reported value for c in [46] is actually the k value, and the reported value for k is in fact the c value. The mean wind speed (7.81 m/s), and the Weibull scale (7.81 m/s) and shape parameters (4.32) at Lamberts East, Barbados [46], are comparable to the corresponding ranges determined in this study which are 7–8 m/s, 8–9 m/s, and 4.0–4.5, respectively. The 7–8 m/s mean wind speed range when extrapolated to 55 m using the power law exponent of 1/7, becomes 8.9–10.2 m/s, which is only about 1 m/s higher than the in-situ mean wind speed.

According to the point-wise wind measurements in the Netherland Antilles and the power law, the reanalysis data appear to be sufficient for determining the mean average wind speeds at wind turbine hub heights. The Netherland Antilles were possibly the first Caribbean islands to make use of wind energy technologies [55]. The mean wind speed at the Playa Kanoa wind park, Curaçao was between 9.0 and 9.5 m/s at 48 m hub heights [55] and at Vader Piet, Aruba, it was approximately 10 m/s at 65 m hub heights [56]. The derived annual average wind speed over Curaçao and Aruba is in the range 7–8 m/s which when extrapolated to 48 m and 65 m heights using the power law exponent 1/7 becomes 8.8–10.0 m/s and 9.1–10.5 m/s, respectively.

Mean wind speeds derived from the reanalyses also provide comparable estimates of the mean wind speeds at greater heights over the Greater Antilles. Wind speeds reported or estimated in the Dominican Republic [9] at 30 m level, Jamaica [55] at the 40 m level, and Cuba at 50 m level [10] are in the ranges 6.1–8.9 m/s, 7.2–8.3 m/s, and 5.6–7.0 m/s, respectively. Extrapolation of the 6–7 m/s range obtained in this work gives 7.0–8.2 m/s at the 30 m level, 7.3–8.5 m/s at the 40 m level, and 7.6–8.8 m/s at the 50 m level. It is clear that the extrapolated reanalysis ranges are comparable to the reported wind speeds.

Spatial variations of statistical parameters derived from the reanalysis data show similar variations as those derived from satellite data, and WPDs are comparable. In general, c and k are high in the southern Caribbean, low at higher latitudes, and very high in the vicinity of the CLLJ region. This spatial variation is reflected in Monahan's [14] c and k plots which were derived from a 7 year QuikSCAT global satellite dataset. For the CLLJ region, Monahan's maps show that scale factors were in the 9–11 m/s range. Another global wind energy study using QuikSCAT data was carried out by Liu et al. [15]. The power density of the CLLJ region was in the range 370–880 W/m^2 for the period 2000–2007 (Fig. 3, [15]) and contains the WPD range from the reanalysis data, 400–700 W/m^2. Unlike satellite data, the reanalysis data are not 'contaminated' by precipitation, and have a higher temporal resolution with its four times daily observations versus daily temporal resolutions for satellite data.

Elliott et al. [12] used monthly averaged ship wind data on a $1^\circ \times 1^\circ$ grid from the 1940s to 1970 to map the wind resources in the Caribbean and Central America. The WPDs for Barbados and Saint Lucia in [12] were in wind power classes 4–6, that is, 200–400 W/m^2, and for the Dominican Republic, part of Hispañola, it was in the 5–7 class or 250–600 W/m^2. The corresponding WPDs in this work are within the ship data ranges at 300–400 W/m^2 and 200–300 W/m^2, respectively. The narrower ranges of this work may be due to the larger k values derived here, 2.5–4.0, versus 1.75–2.50 of [12]. The differences in k-values may be due to the use of monthly wind speed data in Elliott et al. [12] compared with six-hourly wind data in this work.

3.8. Implications

We have shown that the NCEP/DOE reanalysis 10 m wind data can be used for general assessments of the wind resources of regions, such as the Caribbean, where a dense network of high-quality in-situ data are unavailable. The wind power densities in some parts of the Caribbean decrease from the dry season to the early rainy season. The current wind climate may also vary by as much as 92% depending on the year, season, and month. In addition, the regional wind speed and wind power density appear to be increasing. The NCEP/DOE reanalysis wind data may be suitable to provide boundary and initial conditions to dynamical models for the production of high resolution wind maps. However, care has to be taken in selecting a normal wind period to avoid a gross overestimation of the wind resources.

Acknowledgments

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